PART VI

SINGLE VERSUS BINARY STARS

DUPLICITY OF Be STARS AS SEEN FROM ONDŘEJOV

(*Review Paper*)

PETR HARMANEC and SVATOPLUK KŘÍŽ
Astronomical Institute of the Czechoslovak Academy of Sciences, Ondřejov, Czechoslovakia

Abstract. Observed Be stars are considered to be interacting binaries undergoing mostly case B mass exchange. Their observed properties can be explained satisfactorily as the consequences of different modes of mass transfer. Suggestions for further observational and theoretical studies to verify or to disprove the hypothesis presented here are briefly outlined.

1. History

Although the similarity of Be envelopes to the disks observed in some close binaries with hydrogen emission lines had been pointed out by Struve and other astronomers as early as the 1930's, the concept of the possible binary nature of Be stars appeared only after numerical studies of mass exchange in close binaries performed by several teams (for review see, e.g., Plavec, 1970a; or Paczyński, 1971) became available.

Cowley (1964) in her detailed spectroscopic study of AX Mon interpeted this shell star as an interacting binary. In 1968, at the symposium on 'Mass Loss from Stars', Kříž (1969) suggested that the shell star ζ Tau may be a result of case B mass exchange. At the same symposium, Plavec and Horn (1969) offered a similar interpretation of V367 Cyg. Plavec (1970b) pointed out that the excess angular momentum, brought to the mass-gaining star by the infalling matter, is high particularly for case B mass exchange and may lead to the formation of an envelope around this star. He remarked that some shell stars could be formed by this process. In 1971, Harmanec, Koubský and Krpata in Ondřejov started systematic observations of selected shell stars in an effort to detect possible duplicity of these objects. They succeeded in disclosing periodic radial-velocity changes of 88 Her and 4 Her, which were confirmed later by American, Canadian and French observations (see Harmanec *et al.*, 1972a, b, 1973, 1974, 1976; Doazan, 1973; Heard *et al.*, 1975). Also Peters (1973), Hutchings and Redman (1973) and Kříž (1973) interpreted (on the basis of new spectroscopic observations) the Be stars HR 2142, HD 187399, and β Lyr, respectively, as case B mass-exchanging binaries. Harmanec *et al.* (1972b) suggested therefore that the possibility be considered tentatively that *all* shell stars are interacting binaries. Plavec (1973) objected against such a general hypothesis and pointed out some problems of binary interpretation for o And, ζ Tau, φ Per and several other shell stars. Nevertheless, the team of Plavec, Peters and Polidan at Los Angeles has also been studying very thoroughly the possible evolutionary connections between Be stars and binaries (cf. Plavec *et al.*, 1973a; Polidan *et al.*, 1973). In recent years, their observational effort has been particularly directed to infrared spectroscopy. Very recently Kříž and Harmanec (1975) published a completely general hypothesis about the binary nature of all Be stars. The rest of this paper is devoted to the outline and further development of this hypothesis.

A. Slettebak (ed.), Be and Shell Stars, 385–400.

2. Duplicity of Be Stars

Let us consider the appearance of case B mass-exchanging systems. It is necessary to mention that most of the available computations deal with conservative cases of mass exchange (with no mass and angular momentum lost from the system). Concerning the loss of angular momentum, Wilson and Stothers (1975) have estimated that the part of this loss transformed into the increase of the rotation of the mass-gaining component cannot change the sign of the expected period change $\mathrm{d}P/\mathrm{d}t$. No reliable estimate of mass loss is available, however. The peak rates of mass exchange in case B are very high in some cases and a substantial mass loss from the system cannot be excluded. If it really occurs, such mass loss can be self-accelerating (because the size of the binary system shrinks) and can lead to the rapid formation of a contact system (Van den Heuvel and De Loore, 1973). Plavec *et al.* (1973b) analysed this problem and concluded that some modes of mass loss can *decrease* the actual rate of mass transfer very substantially and thus serve as a regulating mechanism for the whole process. The actual course of mass exchange may then be qualitatively similar to the corresponding conservative case. Thus, the situation is not very clear and we must admit that the lack of our knowledge of actual mass and angular momentum loss from interacting binaries is probably the weakest point of all the considerations regarding the consequences of large-scale mass transfer in binaries. At the moment, we can only accept the observed existence of long-period systems with clear signs of continuing mass transfer as an empirical proof of the fact that mass and angular momentum loss from the system is not in most cases so substantial as to change the sign of $\mathrm{d}P/\mathrm{d}t$. If so, available computations provide us with a qualitatively good picture of mass-exchanging systems. Since the first, rapid part of the mass transfer is at least several times shorter in duration than the rest of the mass exchange, we can expect that the later stages of mass exchange, when the role of the components is already interchanged, are statistically the most significant. We therefore should observe mostly long-period systems (10^1–10^2 days) with less massive mass-losing components. These components should be at their limit of stability (usually at the Roche limit). Mass-gaining components of such systems are expected to be essentially unevolved B-type (or A-type) stars with very small relative radii. Computations indicate typical mass ratios of 0.1–0.2; Roche lobes around mass-gaining stars are therefore very large and allow the formation of very extended envelopes within them. Dynamical considerations show that the formation of such envelopes by mass transfer is indeed very probable (cf. Lubow and Shu 1975). Hydrogen emission and shell lines may originate in such envelopes.

As a consequence of relatively large masses and long periods, the semi-amplitudes of the radial-velocity curves of mass-gaining components must be very small, in many cases even on (or below) the limit of detectability.

A wide range of spectral types of mass-losing stars must be expected depending on initial parameters such as masses of the components, mass-ratio, evolutionary age, etc. In neither case, however, should the spectral type of the mass-losing component be earlier than that of the mass-gaining star. In some cases, the spectrum of the mass-losing component may be dominant, but more frequently, the mass-gaining star will be the brighter of the two in the visual part of the spectrum.

When observed spectroscopically, similar systems may appear as single Be stars rather than binaries.

Case B mass exchange proceeds on the Kelvin time scale (10^3–10^6 years) and the existing computations do not describe possible changes taking place on the dynamical time scale which, however, is observationally most interesting. Thus, the possible dynamical effects must be considered separately. We can start with the analogy with other types of interacting binaries. Biermann and Hall (1973) discussed a possible mechanism of cyclic changes in the rate of mass transfer between binary components connected with the dynamical instability of the surface convective layers of the mass-losing star. Their theory was successfully applied by Hall (1975) to explain alternate period changes of U Cep.

Available observational data clearly indicate the existence of several modes of mass transfer:

(i) Continuous steady-state transfer (β Lyr, SV Cen)
(ii) Non-continuous transfer proceeding in bursts (novae)
(iii) Variable transfer (U Cep, SW Cyg).

A typical time-scale of non-steady events is 10^0–10^1 years, i.e. similar to the time scale of the long-term variations of Be envelopes. This led us to the idea of considering tentatively three analogous modes of mass transfer in Be binaries.

Recent progress in the hydrodynamical treatment of gas dynamics in close binaries enables us to predict roughly the structure of circumstellar matter in binary stars. Let us consider a stream of gas which begins to flow from the conic surface of the mass-losing component in the neighbourhood of the Lagrangian point L_1 towards the other star. As already mentioned, the relative radii of mass-gaining stars in case B mass exchange are invariably very small. Consequently, the stream does not strike the surface of the mass-gaining component, but proceeds to orbit asymmetrically around the star and interacts with itself. This interaction produces a deflection of the primary stream, followed by a change in the returning stream and so on. According to Lubow and Shu (1975), the subsequent transient behaviour may last for hundreds to thousands of orbital periods. During this phase, a density maximum can be formed above the advancing hemisphere of the mass-gaining star, such as indicated by the computations of Prendergast and Taam (1974). If the gas outflow from the contact component continues, the envelope around the mass-gaining star eventually becomes so dense as to represent a 'solid wall' to the incident stream. This steady-state situation results in the formation of a very nearly symmetrical envelope, the inner parts of which spiral slowly in toward the underlying star.

On the other hand, if the mass flow between components were to vary substantially within several years (being very weak or absent in some intervals), the transient behaviour of the envelope and its variable asymmetry might be rather typical of such systems (for a binary with $P = 50$ days, for example, 100 orbital periods represent 13.7 years). Keeping the above considerations in mind, we can now discuss the expected properties of the three idealized types of Be binaries.

2.1. TYPE 1: STEADY-STATE MASS TRANSFER BINARIES

The density of gaseous streams in case B mass exchange may be high enough for these streams to produce observable effects. Observationally, we can expect (provided $i \neq 0°$):

(i) Double emission lines arising in the envelope around the mass-gaining star.

(ii) Emission from the stream which can manifest itself by some asymmetry of the observed profiles or by periodic V/R variations (with a period equal to the orbital period).

(iii) Hydrogen absorption lines, which are frequently used to derive the radial-velocity curves, will contain components which can hardly be separated from the underlying star, the envelope, and (at least in some orbital phases) also the stream. It may result in some of the following distortions of the velocity curve:

(a) The well-known Struve (Barr) effect of observing a curve with spurious eccentricity and $\omega \sim 0°$ due to an artificial increase of the observed velocity by the contribution from the (receding) stream as observed shortly before conjunction of the two stars with the mass-losing component in front. Velocity curves of SX Cas or 4 Her may serve as examples; see Figure 1.

In cases when the mass-losing star dominates in the spectrum, an analogous effect with $\omega \sim 210°$ may occur. There exists indeed a local maximum in Batten's (1968) ω's histogram and we suggest that HD 72754, HD 187399, W Cru, and possibly even 17 Lep, may be examples of such systems, the evidence being particularly strong for HD 72754 and W Cru (see Figure 2). Although no pronounced effect of a similar kind is known for β Lyr, it is interesting to note that also its velocity curve accepted for Batten's (1967) 'Sixth Catalogue' has $\omega = 217°$.

(b) The absolute dimensions of the systems in question are so large that different spectral lines from the stream may arise effectively in somewhat different parts of the stream. Provided the binary is not eclipsing, the effect of inclination can contribute and radial-velocity curves of individual lines (affected by the Struve effect) may differ one from another in the semi-amplitude and in the time of maximum velocity. This is because when a line arises from a more extended region of the stream, its contribution (in projection against the stellar disk) will be maximum closer to the conjunction of the stars (provided, of course, $i \neq 90°$) when the projected velocity of the stream is higher, and consequently, the maximum of the velocity curve occurs later. If mean velocities of several lines are used in such cases, the above effect contributes again to the scatter of the velocity curve, thereby decreasing its reliability.

(c) As already mentioned, it is quite possible that (especially in systems with a large mass exchange) a fraction of the gas escapes from the system. Although the detailed mechanism is not known as yet, it seems that this material can form an envelope around the whole system. In favourable cases, parts of this envelope projected against the disk of the brighter component may produce shell-type absorptions observable in the spectrum. Using a simplified assumption that the outer envelope has the form of a circular ring revolving around the centre of gravity of the two stars, we found that the radial velocity derived from the shell lines of this envelope follows the velocity curve of the brighter component of the binary, but with a substantially smaller amplitude. The following relation holds at any phase

$$\frac{RV_e}{RV} = \sqrt{\frac{A^3}{d^3}},$$

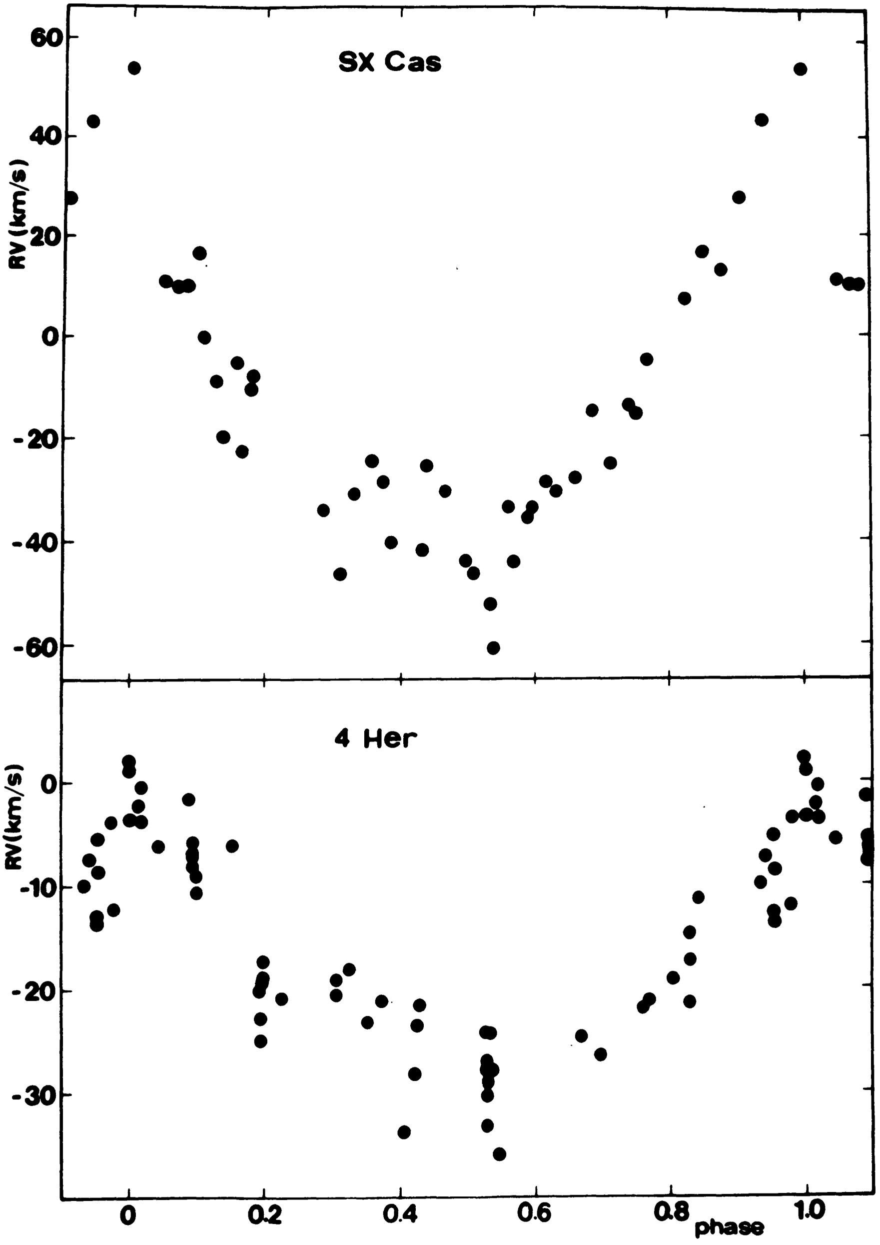

Fig. 1. Examples of the Struve effect on the velocity curves of SX Cas (Struve, 1944a) and 4 Her (Heard *et al.*, 1975).

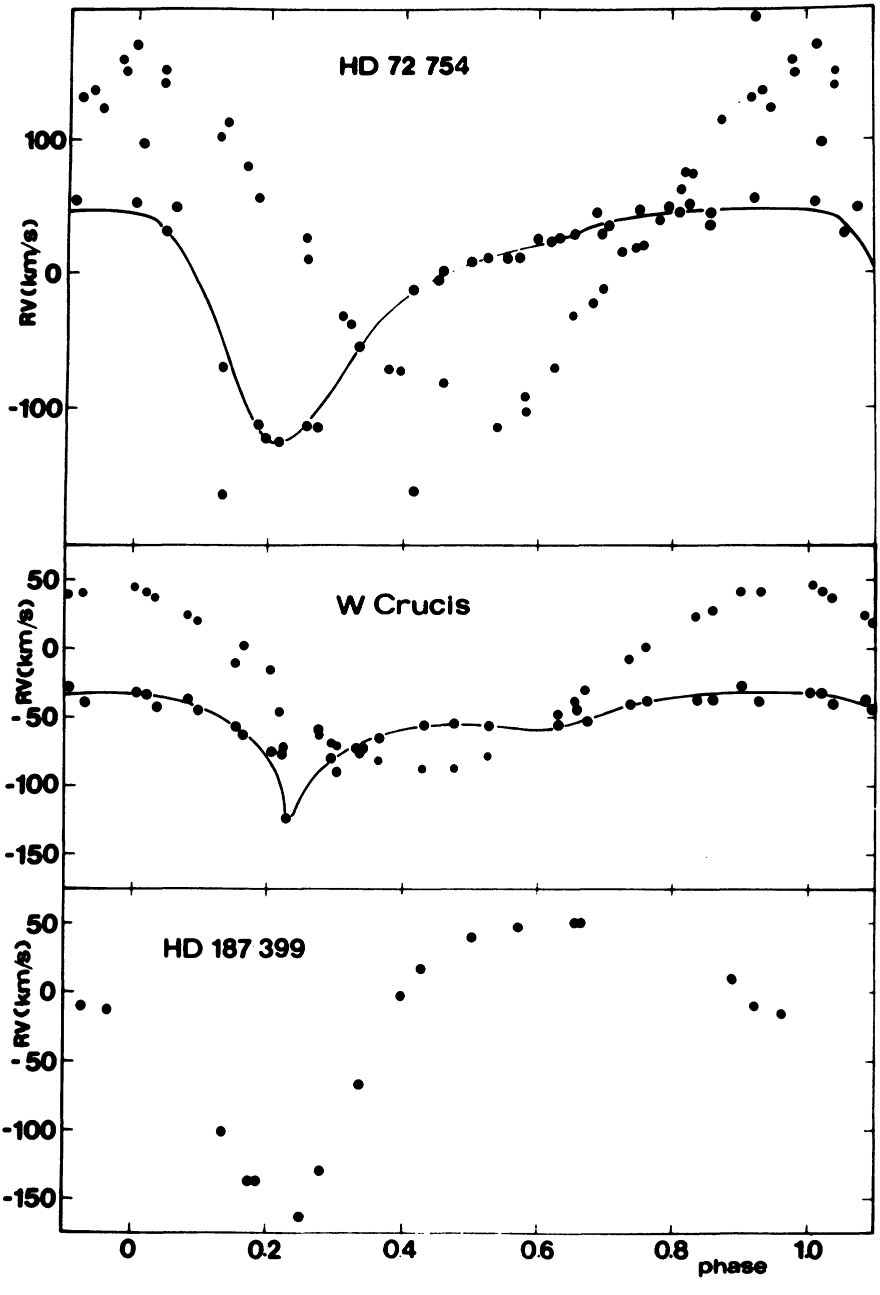

Fig. 2. Examples of the distortion of the hydrogen velocity curves (filled circles) of mass-losing components by absorption in gas streams: HD 72754 (Thackeray, 1971), W Cru (Woolf, 1962) and HD 187399 (Hutchings and Redman, 1973). In the first two cases, the metallic velocity curves of mass-losing components, free of the distortion, are also shown (by open circles).

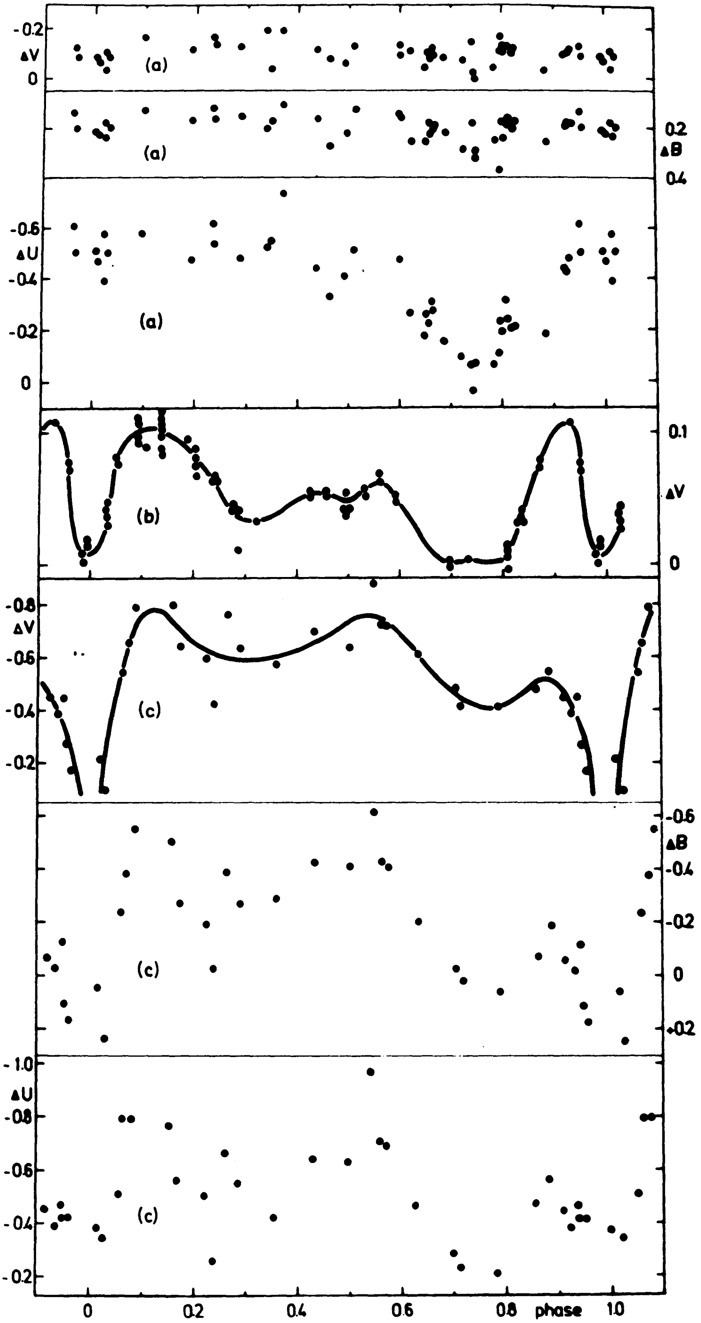

Fig. 3. Photoelectric light curves of AX Mon (a) (Magalashvili and Kumsishvili, 1969), HD 187399 (b) (Hutchings and Redman, 1973) and W Ser (c) (Lynds, 1957).

where RV_e and RV denote the radial velocity of the envelope lines and of the star, respectively, A is the distance between the centres of the components, and d is the effective radius of the outer envelope (we have found a small error in a similar formula by Thackeray, 1971). Lines of the outer envelope with this behaviour are known for HD 72754, V 367 Cyg and W Ser. The presence of an outer envelope is detectable also in the systems β Lyr, HD 187399 and W Cru. In these cases, the velocity changes of the envelope lines are not so clearly visible; rather, a slight expansion prevails. Notably, all of the systems just mentioned show different signs of a very strong mass transfer (for most of them, the *mass-losing* component dominates in the spectrum).

Let us now consider possible photometric effects of circumstellar matter. If the gas stream is dense enough to produce continuous absorption, we can expect a broad minimum in the light curve of the system in or shortly after the elongation with the mass-losing component approaching. Such broad minima are indeed observed (around photometric phases 0.75–0.85) in the light curves of AX Mon, HD 187399 and W Ser (see Figure 3).

For eclipsing systems, additional effects can be expected, such as asymmetry of the primary minimum due to the gas stream, or an ultraviolet excess in the primary minimum caused by the light from the (partially uneclipsed) envelope around the mass-gaining star. Such effects were demonstrated by Hall and Garrison (1972) in the *UBV* light curves of the Algol binary SW Cyg.

2.2. TYPE 2: BINARIES WITH NON-CONTINUOUS MASS TRANSFER GOING IN RAPID BURSTS

If mass transfer between binary components occurs in rapid bursts, the duration of which is at least one order of magnitude shorter than the orbital period, then the ejected cloud of matter will form an elliptical ring around the mass-gaining star during several orbital periods. The behaviour of this ring can be followed approximately by means of the restricted three-body problem. We followed a particular case in a system with the mass-ratio 0.1 (which is rather typical for the final stages of case B mass exchange) in the non-rotating frame of reference with the origin in the centre of the mass-gaining star (see Figure 4). The gradual apsidal motion of the ring due to the attractive force of the mass-losing component is clearly visible. We estimated that the period of this apsidal motion corresponds to 24 binary periods. Considering binaries with $P = 50$, 100 and 1000 days, we arrive at 3.3, 6.6 and 66 years, respectively, for the period of apsidal motion of the ring. This fits well with the typical 'periods' of cyclic long-term variations observed in many Be stars. The hypothesis of duplicity of Be stars provides us therefore with a physical background for the model of an elliptical ring (originally suggested by Struve, 1931; and McLaughlin, 1961) which has recently been developed by Huang (1973) and successfully applied by Huang (1973) and Albert and Huang (1974) to observations of the Be stars 105 Tau, HD 20336, 25 Ori and β^1 Mon.

We think that probably the best known example of the presence of an elliptical ring is in the Be binary ζ Tau. The orbital period of the system is 133 days and the semi-amplitude of the velocity curve of the B2e component $K = 9$ km s^{-1}. Delplace

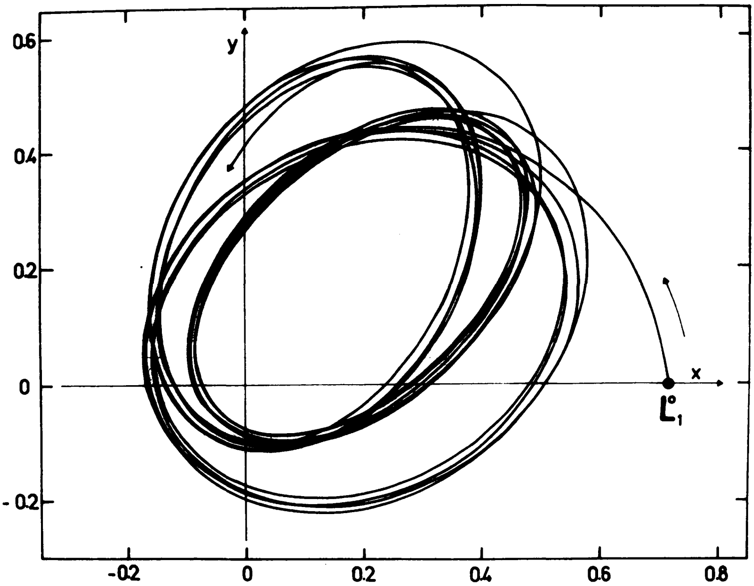

Fig. 4. Evolution of the orbit of a gaseous cloud formed by rapid ejection of matter from the vicinity of the inner Lagrangian point L_1. A non-rotating frame of reference is used. L_1^0 denotes the position of the Lagrangian point at the moment of ejection.

(1970) showed that (after some event in 1958) the lines of the envelope had followed a sinusoidal velocity curve with $K = 60$ km s^{-1} and $P^* = 6.8$ years during the period from 1960 to 1967, with the binary motion with $K = 9$ km s^{-1} still detectable along this long-period curve. Considering the long change as a consequence of the formation of an elliptical envelope, we obtain a reasonably good agreement between the observed values

$$P^*/P = (365 \times 6.8)/133 = 19, \qquad \text{and } K^* = 60 \text{ km s}^{-1}$$

and their theoretical predictions

$$P^*/P = 24, \qquad \text{and } K^* = 63 \text{ km s}^{-1}.$$

Very probably, the tidal forces will tend to circularize the ring so that the long-term variations do not repeat with exactly the same period and may gradually cease after several cycles, provided no new outburst occurs in the meantime.

2.3. TYPE 3: BINARIES WITH VARIABLE MASS TRANSFER

This type represents an intermediate case between the two previous cases. The periods in which mass transfer is strong and weak (or completely absent) are comparable and alternate on a time scale of years. Stars alternating between Be and B phases may belong to this type, e.g., 4 Her, Pleione, 88 Her, *o* And and some others. Observationally, these objects can exhibit some strictly periodic variations in intervals when mass transfer is acting similarly to those of Type 1.

Some additional effects can be observed however:

(a) As already mentioned, the envelope around the mass-gaining component can be notably asymmetric in non-stationary cases and a density maximum can exist above the advancing hemisphere of the star. As indicated by computations of Prendergast and Taam (1974), this dense material moves slowly towards the underlying star. Harmanec (1976) called attention to a consequence of this effect:

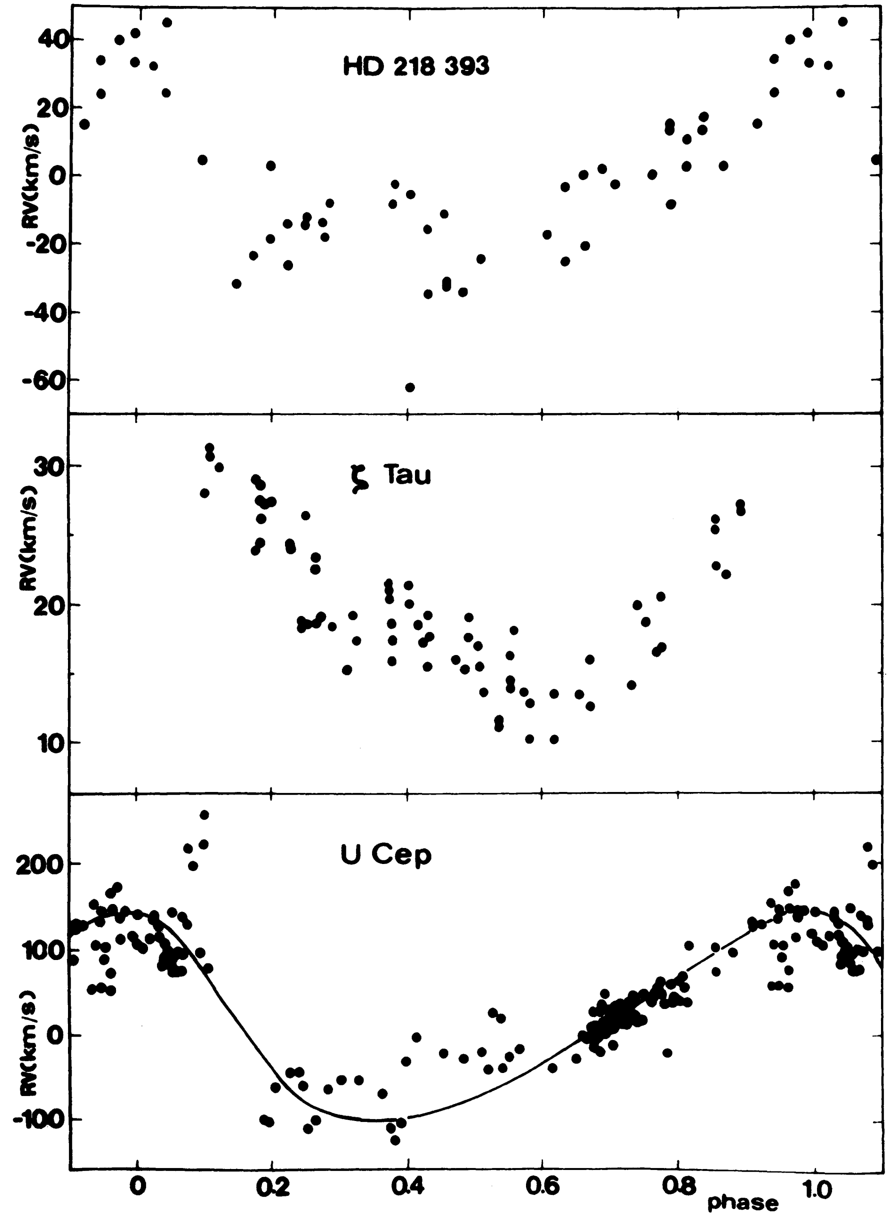

Fig. 5. Examples of the hump on the velocity curves of Be stars HD 218393 (Struve, 1944b) and ζ Tau (Hynek and Struve, 1942) and of the well-known eclipsing binary U Cep (Batten, 1974). Different symbols are used to denote different observed cycles.

line absorption in this part of the envelope, as seen in appropriate orbital phases, may cause a weaker effect similar to the Struve effect: a hump on the velocity curve in the neighbourhood of the minimum velocity. He demonstrated that the effect is indeed observed in many velocity curves of very different kinds of objects. HD 218393 or ζ Tau can serve as examples of the effect among Be stars (see Figure 5). It is important to realize that, under non-stationary conditions, the strength and the position of the density maximum can vary very sensitively, thus causing irregular variations of the shape of the velocity curves. This may even result in the failure of an attempt to establish a period of velocity changes in particular cases (this probably happened in the case of HD 218393).

(b) The density maximum may in some cases even produce photometric effects: a broad shallow minimum around photometric phases 0.2–0.4. Light curves of HD 187399 and W Ser seem to display this effect (see Figure 3).

In addition to the changes correlated with the orbital period, the systems with variable transfer will certainly exhibit (often even more pronounced) long term spectral, light, and colour variations.

When the contact component of such a system becomes stable against mass loss and the mass exchange ceases for some time, the further behaviour of the gaseous envelope around the mass-gaining component probably depends on the duration of the previous mass-exchange period. If this period was relatively short and the envelope still has the form of an elliptical ring, cyclic V/R and velocity variations similar to those of Type 2 binaries can be expected. In the case of a long duration of the previous mass-exchange period, however, when the envelope is almost circularized already, no such variations should occur. Only some effects of a gradual dissipating of the envelope may be observed.

It must be stressed that the three types just described were introduced only to explain different possible effects of mass transfer. We feel that Type 3 of variable mass transfer is probably the most frequent among real Be binaries and that the two other types are idealized limiting cases only which, however, will illustrate possible essential differences in the behaviour of circumstellar matter under different conditions.

In real systems, even more complicated situations may be possible.

It cannot be excluded, for example, that rapid bursts occur even in systems with continuous mass transfer so that an elliptical ring is formed 'in addition' to the existing smaller envelope. In fact, we have to assume such a situation in the case of ζ Tau for which some effects of continuous transfer were detected in the past.

3. Observed Variations of Be Stars and their Possible Causes

It may be useful now to summarize the observed types of variations of Be stars and to comment on their possible causes. They are as follows:

3.1. SPECTROSCOPY

3.1.1. *Long-term Spectral Variations* (time-scale 10^0–10^1 years)

(a) Alternate, mostly irregular, changes in the intensity of emission and shell lines, sometimes a complete disappearance of these lines. Such changes may reflect variations in the intensity of mass transfer between components caused possibly by the dynamical instability of the outer convective zone of the mass-losing star. Though a complete theory of this phenomenon is still lacking, the variability of mass transfer between binary components is well established in the case of Algol binaries (variable Struve effect, $O-C$ diagram of alternate period changes and recent appearance of emission lines in the spectrum of U Cep may serve as a good example).

(b) Cyclic V/R and velocity variations with transient periods of several years. These agree well with the model of an elliptical rotating envelope which we have already discussed.

3.1.2. *Periodic Velocity, V/R and Profile Variation* (time-scale 10^1–10^2 days)

In our opinion, these changes reflect directly or indirectly the orbital motion of the Be binary. The V/R variations of this type are probably caused by the asymmetry of the Be envelope connected with the presence of a gas stream. They are, similarly to the long-termed V/R variations, in phase with the velocity curves. Concerning the velocity changes, it is important to realize that in many cases they can reflect mainly the contribution of the stream (the Struve effect), the amplitude of the velocity changes of the star itself being very small. Even such a curve (or the observed V/R variations) can, in principle, serve to derive the orbital period. It is necessary to realize, however, that in intervals when mass transfer is absent one can observe a *constant* radial velocity which is more negative than the 'systematic' velocity of the previously observed curve. Quite possibly, this is also the case for 4 Her.

3.1.3. *Rapid and Ultrarapid Spectral Variations* (time-scale: minutes–several days)

An increasing effort has been made in recent years to detect rapid spectral variations of Be stars. For several reasons, this problem is very delicate. We personally are not convinced that every rapid variation announced so far is indeed well established. The unclear situation may be illustrated by the following examples:

(a) Ringuelet and Machado (1974) reported rapid periodic velocity variations for π Aqr with a period of 0.087 days. During one week in October 1973 Haefner *et al.* (1975) performed simultaneous spectroscopic, photometric and polarimetric observations of this star and detected no rapid variations from minutes to days. In particular, a periodogram of their velocities and the velocities of Ringuelet and Machado did not reveal any significant period.

(b) Hutchings *et al.* (1971) reported ultrarapid variations of the Hα profile of κ Dra, detected by TV techniques. Nordh and Olofsson (1974) followed the star for three nights by means of narrow-band Hα photometry (one narrow and two broad-band filters) with 10–15$^{\mathrm{m}}$ time-resolution. No changes were detected. Accordingly, we leave the problem of rapid spectral variations for future investigation.

3.2. PHOTOMETRY

Curiously enough, systematic photoelectric observations of Be stars are very rare so far, although they are urgently needed. Consequently, it is hard to classify the light changes of Be stars. Available observations indicate the presence of long-term light and colour variations in many cases but nothing definite is known so far. To the best of our knowledge, no clear correlation between photometric and spectral changes has been found as yet.

Probably the best documented are the periodic changes reflecting the binary motion: light curves of eclipsing binaries and eclipses of stars by gaseous streams (see, e.g. AX Mon or HD 187399, Figure 3). Rapid photometric variations (shorter than 1 day) with transient periods and variable amplitude are well documented in several cases – see, e.g. EW Lac (Walker, 1953; Lester, 1975) or V932 Aql (Lynds, 1960). It would be tempting to speculate about the possible similarity of these variations to the flickering of novae but, clearly, more data must be accumulated before a more serious analysis can be made.

Lester (1975) explains the photometric variations of EW Lac as temperature changes in the atmosphere connected with some sort of pulsation and refuses the model of a dark spot originally suggested by Walker (1953).

4. Suggestions for Further Investigation

Finally, we want to mention briefly which further studies would be desirable in our opinion to confirm or to disprove the outlined hypothesis and to improve our understanding of Be stars in general.

Probably the weakest point of the present reductions of observed data is the semi-qualitative and partly intuitive character of the present-day theories. No complete physical theory of processes taking place in Be envelopes and gaseous streams between binary components is available.

Several very formidable tasks must be solved:

(1) The complete hydrodynamical solution of the gas dynamics in binary stars. Recent progress in this field is very promising (Prendergast and Taam, 1974; Lubow and Shu, 1975) but the available results are still not sufficient. For example, Prendergast and Taam published their computations for only one set of binary parameters corresponding to U Cep (i.e. the mass-ratio $m = 0.49$ and the relative radius of the mass-gaining star $r_1 = 0.19$). In their case, most of the material strikes directly upon the mass-gaining star and only a small fraction of it contributes to the formation of an envelope. At least one other computation with the parameters relevant for a typical Be binary, say $m = 0.1$ and $r_1 = 0.05$, would be highly desirable. Moreover, non-stationary solutions are necessary to study the long-term variations, formation of an elliptical ring and so on.

(2) A complete theory of line formation in circumstellar matter (including non-LTE populations of atomic levels, heating of the envelope, etc.) based on the hydrodynamical solutions of gas dynamics.

(3) An improved analysis of the light curves of eclipsing binaries, taking into account the effects of circumstellar matter.

Only after the above-mentioned problems have been satisfactorily solved, is a reliable quantitative analysis of line profiles, radial velocities, and light changes, and derivation of absolute physical data for individual systems possible. At the moment, such data are, in fact, completely lacking. For any known Be binary (perhaps only with the exception of β Lyr) it is not known with a reasonable certainty, for example, whether or not the mass-losing component fills the corresponding Roche lobe, and so on.

Before the complicated theoretical problems are solved, a lot of work can be done observationally. The following items are what we consider most desirable:

(1) Systematic spectroscopic observations of selected Be stars in a wide spectral range with the highest dispersion possible.
(2) Publishing and analysing radial velocities of individual lines, not just mean values.
(3) Systematic photoelectric photometry of all the brighter Be stars, aimed at discovering possible relations between spectral and light changes and, possibly, disclosing new eclipsing systems among Be stars.
(4) Checking the suspected duplicity of Be stars, for which the (supposedly orbital) period and therefore approximate dimensions of the system are known, by means of new observational techniques such as lunar occultations or speckle interferometry.
(5) Accumulating the most complete and best possible data for the known eclipsing Be binaries β Lyr, V367 Cyg, W Ser, W Cru, RX Cas, SX Cas, UX Mon, HD 72754 and HD 187399, for which a future comparison of observations and theory may be most promising.
(6) Continuing in the effort to detect rapid variations of Be stars. To detect and to follow systematically possible rapid variations of a known Be binary would be especially interesting as it could help to clarify the question of the possible relation of these variations to the phase of the binary period.
(7) An improved comparative statistics of Be stars and Be binaries among B-type stars, taking into account the transient character of the Be phenomenon, evolutionary effects and other factors, would also be interesting.

References

Albert, E. and Huang, S.-S.: 1974, *Astrophys. J.* **189**, 479.
Batten, A. H.: 1967, *Publ. Dominion Astrophys. Obs.* **13**, 119.
Batten, A. H.: 1968, *J. Roy. Astron. Soc. Can.* **62**, 344.
Batten, A. H.: 1974, *Publ. Dominion Astrophys. Obs.* **14**, 191.
Biermann, P. and Hall, D. S.: 1973, *Astron. Astrophys.* **27**, 249.
Cowley, A. P.: 1964, *Astrophys. J.* **139**, 817.
Delplace, A. M.: 1970, *Astron. Astrophys.* **7**, 68.
Doazan, V.: 1973, *Astron. Astrophys.* **27**, 395.
Haefner, R., Metz, K., and Schoembs, R.: 1975, *Astron. Astrophys.* **38**, 203.
Hall, D. S.: 1975, *Acta Astron.* **25**, 1.
Hall, D. S. and Garrison, L. M.: 1972, *Publ. Astron. Soc. Pacific* **84**, 552.
Harmanec, P.: 1976, to be published.
Harmanec, P., Koubský, P., and Krpata, J.: 1972a, *Bull. Astron. Inst. Czech.* **23**, 218.
Harmanec, P., Koubský, P., and Krpata, J.: 1972b, *Astrophys. Letters* **11**, 119.
Harmanec, P., Koubský, P., and Krpata, J.: 1973, *Astron. Astrophys.* **22**, 337.
Harmanec, P., Koubský, P., and Krpata, J.: 1974, *Astron. Astrophys.* **33**, 117.
Harmanec, P., Koubský, P., Krpata, J., and Žďárský, F.: 1976, *Bull. Astron. Inst. Czech.* **27**, 47.
Heard, J. F., Hurkens, R., Harmanec, P., Koubský, P., and Krpata, J.: 1975, *Astron. Astrophys.* **42**, 47.

Huang, S.-S.: 1973, *Astrophys. J.* **183**, 541.
Hutchings, J. B., Auman, J. R., Gower, A. C., and Walker, G. A. H.: 1971, *Astrophys. J.* **170**, L73.
Hutchings, J. B. and Redman, R. O.: 1973, *Monthly Notices Roy. Astron. Soc.* **163**, 209.
Hynek, J. A. and Struve, O.: 1942, *Astrophys. J.* **96**, 425.
Kříž, S.: 1969, in M. Hack (ed.), *Mass Loss from Stars*, D. Reidel Publ. Co., Dordrecht-Holland, p. 257.
Kříž, S.: 1973, *Nature* **245**, 36.
Kříž, S. and Harmanec, P.: 1975, *Bull. Astron. Inst. Czech.* **26**, 65.
Lester, D. F.: 1975, *Publ. Astron. Soc. Pacific* **87**, 177.
Lubow, S. H. and Shu, F. H.: 1975, *Astrophys. J.* **198**, 383.
Lynds, C. R.: 1957, *Astrophys. J.* **126**, 81.
Lynds, C. R.: 1960, *Astrophys. J.* **131**, 390.
Magalashvili, N. L. and Kumsishvili, J. I.: 1969, *Bull. Abastumani*, No. 37.
McLaughlin, D. B.: 1961, *J. Roy. Astron. Soc. Can.* **55**, 13 and 73.
Nordh, L. and Olofsson, G.: 1974, *Stockholm Obs. Report*, No. 7.
Paczyński, B.: 1971, *Ann. Rev. Astron Astrophys.* **9**, 183.
Peters, G. J.: 1973, in A. H. Batten (ed.), 'Extended Atmospheres and Circumstellar Matter in Spectroscopic Binary Systems', *IAU Symp.* **51**, 174.
Plavec, M.: 1970a, *Publ. Astron. Soc. Pacific* **82**, 957.
Plavec, M.: 1970b, in A. Slettebak (ed.), *Stellar Rotation*, D. Reidel Publ. Co., Dordrecht-Holland, p. 133.
Plavec, M.: 1973, in A. H. Batten (ed.), 'Extended Atmospheres and Circumstellar Matter in Spectroscopic Binary Systems', *IAU Symp.* **51**, 216.
Plavec, M. and Horn, J.: 1969, in M. Hack (ed.), *Mass Loss from Stars*, D. Reidel Publ. Co., Dordrecht-Holland, p. 242.
Plavec, M., Polidan, R. S., and Peters, G. J.: 1973a, A paper presented at the 141st meeting of AAS.
Plavec, M., Ulrich, R. K., and Polidan, R. S.: 1973b, *Publ. Astron. Soc. Pacific* **85**, 769.
Polidan, R. S., Peters, G. J., and Plavec, M.: 1973, A paper presented at the 141st meeting of AAS.
Prendergast, K. H. and Taam, R. E.: 1974, *Astrophys. J.* **189**, 125.
Ringuelet, A. E. and Machado, M. E.: 1974, *Astrophys. J.* **189**, 285.
Struve, O.: 1931, *Astrophys. J.* **73**, 94.
Struve, O.: 1944a, *Astrophys. J.* **99**, 89.
Struve, O.: 1944b, *Astrophys. J.* **99**, 75.
Thackeray, A. D.: 1971, *Monthly Notices Roy. Astron. Soc.* **154**, 103.
Van den Heuvel, E. P. J. and De Loore, C.: 1973, *Astron. Astrophys.* **25**, 387.
Walker, M. F.: 1953, *Astrophys. J.* **118**, 481.
Wilson, R. E. and Stothers, R.: 1975, *Monthly Notices Roy. Astron. Soc.* **170**, 497.
Woolf, N. J.: 1962, *Monthly Notices Roy. Astron. Soc.* **123**, 399.

DISCUSSION

Cowley: You present a model which very nicely fits observed characteristics of some stars, but what is the evolutionary history of these systems? In particular, what are the counterparts of these binaries in earlier evolutionary stages, what are their masses and periods, and do we observe them?

Harmanec: Present Be binaries originate, according to our suggestion, from normal main-sequence binaries with relatively short periods. A system consisting of $5\,M_\odot + 2\,M_\odot$ with an orbital period $P = 2$ days may serve as an illustrative (but surely not the only possible) example. For a great variety of initial masses, mass ratios, and orbital periods, case B mass exchange leads to the formation of a wide system with a mass-gaining star of spectral type B or A enclosed by an extended envelope, i.e., to a Be binary as we understand it. Many 'detached' binaries from Kopal's 1956 catalogue are probable progenitors of future Be binaries. During subsequent evolution, more massive components of these systems expand to their Roche limits and case B mass exchange begins. The first part of the process is very rapid and we have little chance to observe it. Yet, it seems that the recurrent nova T CrB and the eclipsing binary UX Mon may be examples of such systems; their mass-losing components are the more massive components in both cases, which indicates that they are at a very early stage of mass exchange. Continuing mass transfer then leads to the formation of typical semi-detached binaries (U Cep may probably serve as a good example) which represent an evolutionary phase immediately preceding the Be stage. It thus seems that we do observe the counterparts of present Be binaries in all earlier evolutionary stages.

Hutchings: If the ring circularizes over some decades one should see the V/R variations damping in amplitude. What we in fact seem to see is a constant amplitude which suddenly begins and suddenly ends.

Harmanec: I think that observations of long-term V/R and velocity variations do indicate damping in amplitude before the variations cease; see, for example, the cases of HD 20336 or β^1 Mon.

With regard to Plavec's and Peters' doubts regarding the reality of long term V/R variations, I agree completely that with scattered observations you can fail to detect a shorter-period variability. On the other hand, I am convinced that in at least some cases (25 Ori, β^1 Mon, ζ Tau, and 48 Lib) the long-term variations are well documented and real. In my opinion, they differ in their origin from shorter and periodic V/R variations, related to binary motion.

Heap: How did you get your radial velocity curve for the star, ζ Tau? What lines did you use?

Harmanec: The hydrogen shell lines and other shell lines (i.e. silicon).

Heap: What is the inclination of the orbital plane of ζ Tau with respect to the line of sight?

Harmanec: I don't know. The star is not known to be an eclipsing binary; however, no systematic photometry of the object has been performed.

Conti: I agree that you have shown that in at least some cases, a Be star can be the result of a 'Case B' mass exchange. However, there seem to be two difficulties with concluding that all or many Be stars are of this type.

First: the fraction of Be stars is $\simeq 20\%$ of all B stars. The fraction of Be-type binaries is about $\frac{1}{3}$ to $\frac{1}{2}$. So the hypothesized post mass-exchange time scale is $\simeq 60$–40% of the lifetime of the pre mass-exchange time scale. This seems much too long for a disk to remain about a mass-gaining star, since it is a significant fraction of its remaining lifetime.

Second: There seem to be more early B-type Be stars than other types, whereas the mass-exchange hypothesis would seem to produce no dependence of frequency with spectral type. In particular, there should be A-type emission-line main sequence stars. But we do not observe such late stars.

Harmanec: I must confess I do not believe that the present data on the relative number of Be stars and of spectroscopic binaries among B stars are very meaningful. But even if we accept them, the reasoning concerning lifetimes is not as simple as you suggest. It is necessary to take into account the large differences in evolutionary lifetimes along the main sequence. Because during any case B mass exchange the original mass-ratio is more than reversed, the relative fraction of mass-exchanging binaries with primaries of a given spectral type among all Be stars of this spectral type is enhanced. We have published (Kříž and Harmanec, 1975) simple statistical computations which indicate that the observed percentage of Be stars can be explained in this way. I cannot answer your second objection precisely but it seems again that the different evolutionary lifetimes should be considered.

My present position is the following: we have good observational and theoretical arguments to believe that many Be stars are in fact interacting binaries. We therefore suggest serious consideration of the possibility that the Be phenomenon is always caused by mass exchange, along with other existing hypotheses. This assumption may serve as a good working hypothesis to stimulate further investigation of Be stars.

Doazan: What are the final criteria used to determine whether a particular Be star is a binary or not?

Harmanec: To detect a secondary component, either directly in the spectrum, or indirectly, from photometry in the case of eclipsing binaries, or by means of lunar occultations or possibly by speckle interferometry in other cases. Otherwise the evidence is necessarily indirect.

Goldberg: Can you give an estimate of the angular separation of the binaries?

Harmanec: I have not computed this, but it can be estimated from the fact that the typical separation of the components is several hundred solar radii.

Goldberg: I am just wondering whether they are large enough so that there is even a possibility of observing them by speckle interferometry. You cannot do any better than the theoretical resolving power of the aperture. For the Kitt Peak 4-m telescope using visible light this is about $0''.03$.

Cowley: If, on the main sequence these stars were of approximate masses 5 $M_\odot$ and 2 $M_\odot$, and the Be phenomenon is a result of Case B mass transfer from the 5 $M_\odot$ star, then one should observe no Be stars in clusters in which there are stars with $M > 5\ M_\odot$ still on the main sequence.

Harmanec: I used $5\ M_\odot + 2\ M_\odot$ as an illustrative example; case B mass exchange in a system with, say, $12\ M_\odot + 7\ M_\odot$, leads to a similar result. Moreover, P. Hintzen and J. Scott (preprint) consider seriously the possibility that the evolutionary ages of individual stars in a particular cluster need not be the same.

Thompson: The variations of Hα reported in κ Dra by Hutchings *et al.* (*Astrophys. J.* **170**, L73, 1971) are probably partly instrumental effects, principally the instability of the scanning raster of the Isocon camera, used in those observations. Hutchings reports as yet unpublished observations of Hα in κ Dra obtained with a Reticon detector (which is not susceptible to these instabilities) which confirm these rapid variations. Further observations of this type are obviously very important.

Hutchings: As I mentioned in my talk, I am aware of the pitfalls in detecting these effects. However, there are now sufficient independent and different experiments to convince me that they are real.